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Report Title

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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

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TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations:

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
Gabriel LoDolce (sr. technician)	0.38
Emily Ranquist (jr. technician)	0.20
Gabriel Chapel (jr. technician)	0.04
Russel Temple (jr. technician)	0.04
FTE Equivalent:	**0.66**
Total Number:	**4**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Scientific Progress and Accomplishments

Introduction

This report describes work accomplished to assemble equipment for the DURIP equipment grant W911NF-13-1-0316, “DataHawk Flocks: Self-Contained sUAS Modules for High-Resolution In Situ Atmospheric Measurements”. This project developed a portable atmospheric measurement system to support current and future scientific objectives in fine-scale observations of the atmospheric boundary layer, extending up to the tropopause. It was designed to provide a low cost, easily transportable, self-contained pod system that can be shipped anywhere to support field campaigns in virtually any location. The project incorporated the latest advances in DataHawk aircraft design, autopilot hardware and software, and payload sensors.

System Description

1.0 DataHawk 2 Airframe

The older DataHawk 1 airframe was a commercial product designed for hobby use. Although it was very low cost, it did not allow for many of the features that were desired in atmospheric sampling applications. A search of other commercial options did not reveal any other suitable options. Therefore, an airframe was designed from scratch that incorporated all of the desirable attributes and lessons learned from operating the DataHawk 1 in previous field campaigns. Key design features were as follows:

1.1 Safety: Consequences of contact with the vehicle are reduced by several design features. The airframe is a soft resilient form, stiffened by internal spars, so there are no sharp edges or rigid materials involved in contact with the flying vehicle. The motor and propeller are in the rear, with a folding propeller, reducing the chance that the prop would be damaged on landing, or the propeller could come into contact with ground personnel or property. Finally, the mass of the vehicle is small (less than 1.1 kg), and its flying speed is low (between 12 and 24 m/s), reducing the kinetic energy available from contact with stationary objects. Other aircraft fly much faster than this, making the DataHawk essentially a stationary hazard, similar to that of birds.

1.2 Ruggedness: Operation from a wide variety of locations was desired, necessitating a very rugged design that could be launched and landed from unimproved surfaces that may contain obstacles (trees, rocks, etc.). The older design used an expanded polyolefin foam body, which was a rugged material, but the long pointed nose of the aircraft tended to break off on rough landings. The new design incorporated a wide, blunt nose, and used expanded polypropylene foam, which is more elastic. Also, wing spar breakage was eliminated by the use of thin wall stainless steel joiner tubes that enabled the spars to bend forward rather than break in a hard landing. Also, the trailing edges in the old design were very fragile. The new design incorporates very thin fiberglass trailing edges stiffened by foam wedges that are virtually indestructible and bend rather than break. Leading edges are reinforced by fiberglass fiber tape, providing a strong, resilient, yet soft contact area.

1.3 Duration: The older design had a narrow fuselage, designed more for aesthetic appeal than for carrying payload or batteries, limiting the flight duration to about 45 minutes. The new body design is broad and thick, enabling the battery capacity to be tripled. This brings the battery weight to about ½ the total vehicle weight, and resulted in a doubling of the flight duration to about 100 minutes. In turn, this doubled the altitude the aircraft can reach from a ground launch from 2km to 4km, and produced a similar increase factor in range.

1.4 Packaging Efficiency: The old DataHawk design was very difficult to package for shipment, since it was not designed to break down into a small package. The new design explicitly considered this issue, resulting in the ability to package the aircraft in an efficient rectangular volume 12in by 3in by 28in (0.6 cubic feet). This enabled five aircraft to be housed in one reasonably sized crate (16in by 28in by 34in), along with the other ground support equipment. Each aircraft can be assembled or disassembled in about 15 minutes.

1.5 Gust insensitivity: The previous design incorporated swept wings, both for aesthetic appeal but also to provide effective dihedral that makes it easier for hobbyists to fly with radio control (RC). This has the effect of increasing the airframe sensitivity to wind gusts. The new design eliminated the effective dihedral as well as the roll moments from the vertical tail to enhance gust insensitivity, making the vehicle more robust in windy conditions.

1.6 Flexibility for carrying new sensors: The new airframe has a large volume of body foam than can be cut out to house various sensors without sacrificing structural integrity.

1.7 Buoyancy: The use of closed cell, insoluble foam makes the vehicle naturally buoyant.

1.8 Weather resistance: The new vehicle was covered in a thin laminating film using a special consolidating process at the surface to produce a smooth, weatherproof exterior on the vehicle.

1.9 Maintainability: Most any damage can be repaired in the field, either by gluing foam back together, or applying reinforcing tape. However, due to the wear and tear from rough field landings, some attrition is expected, and airframes must be retired at some point. This is ameliorated by the low cost of the vehicle, and the ability to package and ship more than one to a field site to serve as spares.

2.0 DataHawk 2 Autopilot

The original DataHawk autopilot was developed at CU under NSF funding, with the objective of minimizing size and cost, so that many small vehicles could be fielded at low cost. Through initial field campaigns, it was determined that large numbers of vehicles are not needed for most applications, and instead a few vehicles with more processing capability would be more appropriate. Accordingly, a study of autopilot requirements and commercial options was carried out. In the interim since the original DataHawk autopilot was developed, there has been an explosion of commercial autopilot options, facilitated by new lower cost sensors and microprocessors resulting from high-volume markets in gaming systems and cell phones. At the low

cost end of this spectrum, these autopilots have been designed to serve the consumer markets for do-it-yourself drones, and do not provide many extra peripheral interfaces for scientific sensors. Also, although the software for these systems has been tested by a large user community, this does not satisfy the highly variable use-cases and sensor interface requirements envisioned for DataHawk applications. Therefore, to serve the applications of interest, it became clear that another custom autopilot (hardware and software) would be needed. The DataHawk 2 autopilot design incorporates the following features:
2.1 Flexibility in interfacing new sensors: A large number of standard interfaces are brought out to connectors on the processor board, including 3 SPI, 3 I2C, 1 CAN, 6 UART, 8 analog, and 1 digital camera interface.
2.2 Flexibility in changing peripherals: The autopilot is designed as a modular stack, consisting a of processor board, power board, and (one or more) connector boards. Flight sensors (pitot airspeed, pressure altimeter, GPS, gyro/accel/magnetometer) are not integrated on the processor or power boards, since these become obsolete as new versions are developed rapidly for other applications. This way, the processor and power boards need not be modified to support future sensor products. Only the connector board would need to be changed.
2.3 Control over SW and HW for these applications: A custom set of hardware and software provides complete flexibility to implement the flight control and sensor interface algorithms as the scientific applications and operational needs change. This also enables control over these changes to be centralized and managed to prevent unexpected anomalies.
2.4 Expandability for the future: The software architecture was purposefully designed to be open and flexible, so that changes could be easily made without requiring wholesale architecture modifications. This results from a set of lower level utilities and drivers that are general purpose, enabling rapid changes in association of various ports and hardware resources to peripheral sensors. A general purpose data logging and telemetry system was also developed, that could also maintain tight control over sampling rates and synchronization with other data variables. At the higher levels, operational logic is guided by a state machine to reduce the complexity of testing mode transitions, and control is based on a loop structure suited to aircraft dynamics, and a guidance methodology based on vector field atttractors to provide a conceptually simple operator mental model.

3.0 DataHawk ground control station

Existing ground stations have been conventional laptop computers. But even the semi-rugged types are not sufficiently sealed for extended outdoor operations in dust and rain. Also, many of these do not have bright enough displays for operation in direct sunlight. On the other hand, fully rugged laptop computer are extremely expensive and very heavy. The smaller, lighter ones typically only support “small” operating systems, such as Android, making the use of full-featured graphics and analysis software (such as Matlab) infeasible. Also, the display must be large enough to show the wide variety of information needed for flight control and science data. A balance of all these objectives was found in the new R12 rugged tablet from Motion Computing. This runs Windows 8, has a large memory capacity, large bright screen, long battery life, IP65 dust and moisture resistance, and reasonable cost and weight.

4.0 Measurement Systems

Although a variety of measurements can be supported by the flexible design of the airframe and autopilot, the initial measurements consist of:
4.1 Location: A single-frequency GPS provides lateral position with sub-meter resolution and an absolute accuracy of about 10m. GPS solutions are returned at 5Hz, but higher rate position solutions are provided by a fused GPS/IMU system that uses accelerometer information to produce position estimates at 200Hz. Vertical position is less accurate, so pressure altitude is used instead. This is also updated at 200Hz. Long term drift of pressure altitude is corrected in post processing using GPS altitude.
4.2 Temperature: High resolution temperature is provided by a custom “cold-wire” sensor that measures the resistance of a 5¿m diameter platinum wire. This provides a temperature resolution of 0.003C over a range of -60C to +40C, with a thermal time constant of 3ms and an update rate of 700Hz. This is post-flight calibrated using a co-located semiconductor temperature sensor that is slower, but is factory calibrated.
4.3 Humidity: This is measured using a Honeywell HIH5031 sensor that provides an accuracy better than 3%RH over the temperature range of -40C to +40C, for RH between 5% and 95%. The time constant on this sensor is quoted to be 8sec, but it is likely faster in the moving air onboard the DataHawk.
4.4 Wind: This is a combination of measurements of vehicle vector velocity (relative to the ground), a byproduct of the GPS/INS solution mentioned above, and the measurement of the vector relative wind onboard the vehicle. This is complicated by the need to rotate the on-board relative wind measurement into inertial coordinates, which requires an accurate attitude solution. In turn, this requires a rather complex estimation procedure that corrects integrated rate gyro measurements of attitude using magnetometer and gravity vector estimates. The technique used here incorporates the latest research in high-accuracy attitude and velocity estimation. The wind estimation products have not been fully validated against tower-mounted sensors, but predicted accuracy is better than 0.1 m/s.
4.5 Turbulence: Two turbulence parameters have been estimated using the above sensors. The temperature structure parameter CT2 is estimated at very fine resolution by using spectral analysis of data records of cold wire temperature. These spectra are fit in post processing in the inertial subrange of frequencies to determine CT2 for each time record. For example, if the DataHawk is ascending at 1 m/s, and 1 second time records are used, we obtain CT2 variations with a vertical resolution of 1m. The second turbulence parameter that has been estimated is the energy dissipation rate epsilon. This uses a similar spectral analysis procedure in post processing using high rate pitot measurements of airspeed, and provides similar time/space

resolution.

5.0 Ground Support Pod
A total of four ground support pods have been constructed. Each is based on a rugged polyethylene shipping case with wheels that can be handled by one person. Dimensions of 16in by 28in by 34in make it shippable as air passenger luggage (less than 100 linear inches), as well as the weight of just under 100 lbs. This makes transporting the system very flexible, since it can be sent ahead as air or ground cargo, or brought with personnel as accompanied baggage. The pod contains the following components:
5.1 DataHawk storage: Five vertical slots are located in one half of the case to hold disassembled DataHawks. Dividers provide rigid protection for each plane.
5.2 Charging system: A 12 lead-acid battery (dry cell) provides energy for DataHawk battery charging between flights, and for charging the ground station tablet computer. In turn, this 12 battery can be charged from solar panels located in the lid of the case, or by an external generator or car alternator. This system was designed to support continuous operation of a flock of 4 planes flying simultaneously.
5.3 Tools: Special tools needed by the DataHawk are included, as well as a few general purpose tools for general repairs.
5.4 Spares: a small box of DataHawk spares are included to make field maintenance easier.
5.5 Antennas: high gain patch antennas are included, to enable long range communication. The current system uses 900MHz ISM band radios, providing a slant range of approximately 15km. 2.4 GHz telemetry links are also possible.
5.6 Tripods: used to support the telemetry antennas.
5.7 Cables: for connecting solar arrays, car alternator, and laptop chargers, as well as long USB cables for connecting the telemetry antennas to the ground station tablet.

Please see the attached file for photos of this equipment, and a brief description of its use in 3 major field campaigns in June, July, and August, 2015.

Technology Transfer

Use of the DataHawk sensing system in field campaigns has generated significant interest by other scientists in acquiring and using such a system. In particular, the DataHawk system was used to compare in-situ measurements of temperature, humidity, and winds with radar returns from the Shigaraki MUR in Japan, in collaboration with Toshitaka Tsuda, Hiroyuki Hashiguchi, Hubert Luce, Richard Wilson, and Lakshmi Kantha. A second field campaign was conducted at Dugway Proving Ground in Utah, focusing on shear and orography induced dynamics, in collaboration with John Pace, Dragan Zajic, and David Fritts. A third campaign was conducted with this system at the DOE AMF-3 facility at Oliktok, Alaska, to provide routine profiling of boundary layer temperature, humidity, and winds over long durations. This was in collaboration with Gijs DeBoer and Albert Bendure.

Commerical interest in the DataHawk vehicle has been pursued through exploratory work with Trimble Navigation, who are interested in the DataHawk 2 design for a low-cost platform for photogrammetry applications.

DataHawk Flocks Equipment and Campaign Use to Date

Figure 1: Assembled DataHawk 2 aircraft, shown on top of the DataHawk Flock Pod shipping case. Wing span is 52in., gross weight is 1.1Kg, flight speed ranges between 12 and 24 m/s, and duration in level flight is about 100 minutes.

Figure 2: DataHawk Flock Pod, consisting of a shipping case, slots for five disassembled DataHawk 2 aircraft (lower right), solar arrays for battery charging (upper half), and other ground support equipment (tripods, antennas, spares, tools, computer, lower right).

Figure 3: DataHawk Flock used in the June, 2015 campaign in approved airspace at Shigaraki, Japan, comparing radar returns with in-situ DataHawk measurements. Two of the five DataHawks from this campaign are visible in the picture (white planes, left), with equipment from one DataHawk Flock pod. An average of 3 flights per day were conducted over a 10 day period. The pod and batteries were shipped separately by commercial air cargo.

Figure 4: Preparing for a weather balloon drop deployment of the DataHawk 2 at Shigaraki. This enabled flighs up to about 4km above ground level. For these higher flights, higher gain antennas are needed (left). Both 2.4 GHz and 900 MHz ISM bands have been used. 2.4 GHz was necessary in Japan due to frequency restrictions there.

Figure 5: DataHawk deployment in restricted airspace at Dugway Proving Ground, Utah. (This was an official photo taken during the first campaign there in October, 2013. The recent deployment in July, 2015 used the new DataHawk 2 vehicles, and the smaller "pods" described in the project report, rather than the trailer shown here. Offical photos were not taken in the second deployment, and no other photos were allowed on site). Most of the data taken in the June, 2015 campaign were acquired at a site in close proximity to the one pictured here. An average of 4 flights per day were conducted over a 6 day period, using one DataHawk Flock pod of 5 aircraft. Several of these flights utilized simultaneous DataHawk mesurements with 2 planes. The focus of this campaign was measurement of fine-scale turbulence parameters during nocturnal and early morning conditions. The pod was shipped as accompanied baggage on a commercial passenger aircraft, and the batteries were shipped separately.

Figure 6: DataHawk 2 flying in restricted airspace near the Air Force LRR site in Oliktok, Alaska, in August, 2015. An average of 10 flights per day were conducted over a 14 day period. One DataHawk Flock pod with 5 aircraft was used for this campaign. This campaign focused on routine soundings of the boundary layer to measure temperature and humidiy profiles at higher resolution than the current twice-daily balloon sonde soundings at the Sandia ARM facility there. The pod and batteries were shipped ahead of time on commercial air cargo carriers.

Figure 7: DataHawk Flock ground support equipment consists of a ground station laptop computer and a patch antenna (on tripod), providing a very lightweight and portable system. This was very helpful at Oliktok due to the possibliilty of polar or grizzly bears suddently appearing. This occurred once during this campaign, nessitating a quick retreat to the safety of the Air Force radar facility.

Figure 8: DataHawk 2 coming in for a landing at Oliktok Point, Alsaska. Although this site had an airstrip, it was not used for take offs or landings. The DataHawk 2 is launched by a bungee cord, and landed on unimproved surfaces. Here we preferred to land in the tundra just off of the gravel airstrip.